SIX-DEGREE OF FREEDOM MICRO FORCE-MOMENT SENSOR FOR APPLICATION IN GEOPHYSICS

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ABSTRACT

This paper presents the design concept, fabrication and calibration of a six-degree of freedom (6-DOF) turbulent flow micro sensor utilizing the piezoresistive effects in silicon. The proposed sensor can independently detect six components of force and moment on a test particle in a turbulent flow. By combining p-type conventional and shear piezoresistors in Si (111), and arranging them suitably on the sensing area, the total number of piezoresistors used in this sensing chip is only eighteen, much fewer than the forty eight piezoresistors of the prior art piezoresistive 6-DOF force sensor [1]. Calibration for six components of force versus output voltages was carried out. The sensitivities are linear, close to the design values, and high enough to measure the forces and moments expected to act on the particles in turbulent flow in geophysics.

INTRODUCTION

One of the holy grails in geophysical research is reliable simulation technology for the micromechanics of sediment particle, erosion and transport, which are the fundamental processes shaping the land and major factors in flooding phenomena. In work here [2], temporally resolved, high-resolution particle image velocimetry (PIV) has provided the first experimental confirmation of the staggered arrangement of streamwise vortices previously predicted by numerical simulations to occur near the wall of turbulent channel flow. Figure 1 shows a perspective view of coherent vortices over the wall of a turbulent channel flow, measured by stereographic PIV in a cross-stream laser sheet, near the lower wall of a water channel. Isosurfaces of streamwise vorticity are shown in dark and light gray, while low speed fluid is indicated by wire frame. Prominent Reynolds-stress producing events are indicated by black spheres (ejections) and transparent gray spheres (sweeps). In order to investigate the spatio-temporal relationship between near-wall vortices and bed-particles, it is necessary to have micro force sensors with six degrees of freedom (6-DOF) to measure the fluctuating components of force and moment on a particle at the bed of a turbulent channel flow. Such data will be invaluable in verifying simulations of sediment transport.

There have been several approaches to design and fabricate full six-component force-moment sensors. Sinden and Boie [3] introduced some theoretical designs of a planar capacitive force sensor with 6-DOF. However, these designs are more complex than piezoresistive sensors and not advantageous to fabricate with MEMS in terms of fabrication accuracy, reproducibility, and sensor dimension. Grahn [4] invented a triaxial normal and shear force sensor, which used ultrasonic technique as the detecting principle. Okada [1] also reported a planar six-axis force sensor based on the silicon piezoresistive effect. Forty-eight piezoresistors

Fig. 1 Perspective view of coherent vortices over the wall of a turbulent channel flow

are formed at twenty-four places on the upper surface of beams. Large numbers of piezoresistors on beams make the electrical circuit complicated, and result in high power dissipation, wide beams, and consequently, high structural stiffness.

In this paper, the design and fabrication of a micro sensing chip with 6-DOF using only sixteen conventional and two shear piezoresistors is described. One can use this design of sensing chip to fabricate other micro integrated force-based sensors, such as tactile sensors, and micro accelerometers.

CONFIGURATION OF SENSOR

The sensor configuration is shown in Fig. 2. The sensing chip is located inside a test particle so that its centroid coincides with the center of the surface of the sensing chip. The test particle has a diameter of about 8 mm and is made of polyethylene, of which the specific gravity is 0.965, nearly equal to that of water. By this selection of material, the vertical force component (buoyancy force) on the particle is almost eliminated during working. 25μm-diameter

gold wires connecting the sensing chip to the off-chip circuits are isolated and fixed on the surfaces of a base pillar. The sensing chip is completely overload-protected by a protection base located under it. All electrical elements of the sensor are waterproofed by a silicone rubber layer. Forces and/or moments from liquid flow acting on the test particle will be transmitted to the sensing chip via a force transmission pillar placed at the center of the sensing chip.

DESIGN OF SENSING CHIP

Structural Analysis

The dimensions of the sensing chip were tentatively specified based on the expected ranges of force and moment acting, the desired sensitivity, the piezoresistive effect of silicon, the non-buckling condition, and the necessary width of beam for wiring. This model was then analyzed by FEM to investigate more fully the stress field in the structure, and to optimize the specifications of the beam dimensions. Figure 3 shows the finite element model of the sensing chip for numerically analyzing in MENTAT 3.1 software (MARC Research Corp.). Modal analysis was also performed to ensure the sensor can resolve required frequencies in turbulent liquid flow. Finally, the dimensions of each arm of the crossbeam were specified to be: 500 x 120 x 40 μm^3 (L x W x T). The overall sizes of the chip are 3000 x 3000 x 400 μm^3.

Piezoresistors Arrangement and Measurement Circuits

Based on the stress distribution in the crossbeam derived from FEM analysis, piezoresistors were placed and connected so as to maximize the sensitivities to various components of force and moment, and to eliminate the cross-axis sensitivities as shown in Figs. 4. Sixteen p-type conventional piezoresistors, (4-R_{Fz}, 2-R_{Fx}, 2-R_{Fy}, 4-R_{Mx}, and 4-R_{My} to detect Fz, Fx, Fy, Mx, and My, respectively), and two p-type shear piezoresistors (R_{Mz1} and R_{Mz2} to measure the moment Mz), were formed by using impurity diffusion along the central-longitudinal axes on the upper surface of an n-type silicon crossbeam, (Fig. 4). The in-plane principal axes of the piezoresistors were aligned with the crystal directions $<1\overline{1}0>$ and $<11\overline{2}>$ of silicon (111). All conventional piezoresistors were designed to be identical, as were the two shear piezoresistors. The piezoresistive effect of conventional single-crystalline piezoresistors can be expressed as below, [5]:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \quad (1)$$

where $\frac{\Delta R}{R}$ is the relative change of resistance in a conventional piezoresistor due to the longitudinal stress σ_l (i.e. the component parallel to the current flow and electrical field) and transverse stress σ_t. π_l and π_t are the corresponding piezoresistance coefficients. Piezoresistors were arranged far enough from the fixed beam-ends to avoid unexpected stress components, so that the stress status at each conventional piezoresistor is uniaxial, and as a result, $\sigma_t \approx 0$. Thus, Eq. (1) can be rewritten by:
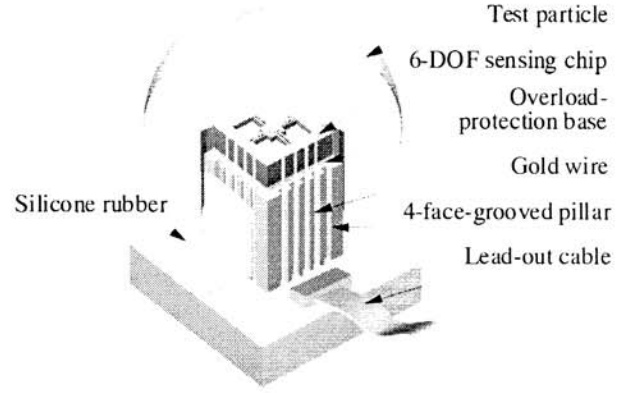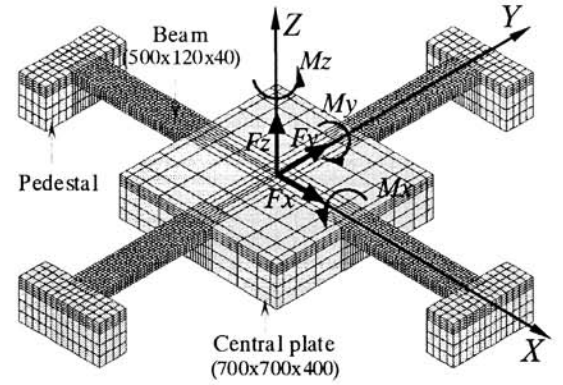

Fig. 2 Configuration of the sensor

Fig. 3 FEM model of sensing chip

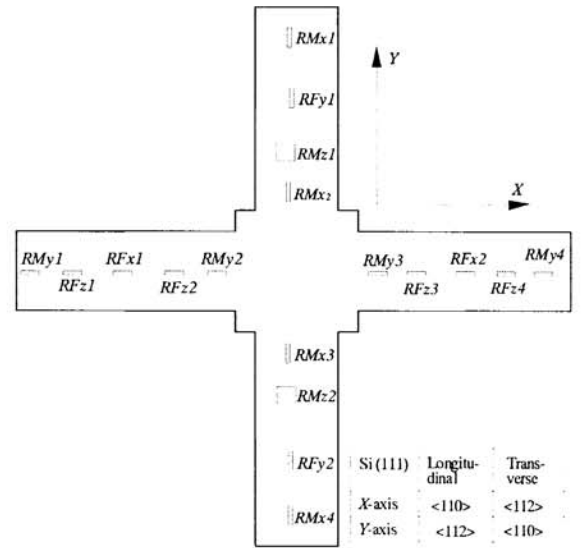| Si (111)	Longitu-dinal	Transverse
X-axis	<110>	<112>
Y-axis	<112>	<110>

Fig. 4 Arrangement of piezoresistors on the crossbeam

$$\frac{\Delta R}{R} = \pi_l \sigma_l \quad (2)$$

The piezoresistive effect of a shear piezoresistor can be expressed as below, [6]:

$$V_{out} = \pi_s \tau_s V_{in} \quad (3)$$

where V_{out} is the output voltage of the shear piezoresistor in response to an in-plane shear stress τ_s (or τ_{xy}), V_{in} is the supply voltage, and π_s is the shear piezoresistance coefficient. Ignoring extremely small dimensional changes of the piezoresistors, the π_l and π_s along the two crystal directions $<1\bar{1}0>$ and $<11\bar{2}>$ can be expressed by, [7]:

$$\pi_{l<1\bar{1}0>} = \pi_{l<11\bar{2}>} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44}) \qquad (4)$$

$$\pi_{s<1\bar{1}0>} = \pi_{s<11\bar{2}>} = \frac{1}{3}(\pi_{11} - \pi_{12} + 2\pi_{44}) \qquad (5)$$

With an impurity concentration of about $5\times10^{19} cm^{-3}$ (typical of our process), $\pi_{44} = 85\times10^{-11}$ Pa^{-1}, [8]. For p-type piezoresistors, π_{11} and π_{12} are sufficiently small in comparison with π_{44}, that they can be neglected. Equation (4) and Eq. (5) are thus approximated by:

$$\pi_{l<1\bar{1}0>} \approx \frac{1}{2}\pi_{44} \; ; \; \pi_{s<1\bar{1}0>} \approx \frac{2}{3}\pi_{44} \qquad (6)$$

Table 1 summarizes the resistance changes of the conventional piezoresistors and output voltages of the shear piezoresistors due to the applied loads. The '+' and '−' signs indicate respectively an increase and decrease, '0' means unchanged and '=' means a similar change in both sign and magnitude in piezoresistors of a corresponding bridge.

Based on the Table 1, the measurement circuits for measuring the five components, (Fx, Fy, Fz, Mx, and My), are created by connecting five parallel detecting potentiometer circuits with a common potentiometer circuit to form Wheatstone bridges sharing a common half-bridge. The common half-bridge resistors are identical and placed side by side on an unstressed region of the chip. To measure the moment around the Z-axis Mz, the voltages of the two shear piezoresistors R_{Mz1} and R_{Mz2} are summed by a summing circuit:

$$V_{outMz} = V_{outMz1} + V_{outMz2} \qquad (7)$$

where V_{outMz1} and V_{outMz2} are calculated from Eq. (3).
The shaded regions in Table 1 indicate where the response of the corresponding bridge is non-zero. A more detailed explanation about the working principle of the sensor was reported by the authors in [9].

FABRICATION PROCESS
The sensing chip was fabricated by micromachining process shown briefly in the following:

Step 1: The starting material was 4-inch n-type (111) silicon wafer with a thickness of 400 μm.

Step 2: A 0.3μm-thick insulator layer SiO_2 was formed by thermal oxidization process.

Step 3: Piezoresistors were patterned so that their principal axes align with the crystal directions $<1\bar{1}0>$ and $<11\bar{2}>$. Boron ions were diffused to form p-type piezoresistors by using spin-on diffusion source (PBF, Tokyo Ohka Kogyo Co., Ltd). Pre-deposition process was performed in N_2 at $1000^{\circ}C$ for 60 min. Then, a drive-in process was done in dry O_2 at $1100^{\circ}C$ for 30 min to activate boron ions in the Si. In order to reduce the temperature sensitivity of piezoresistors, the impurity concentration was controlled at about 5×10^{19} cm^{-3}.

Step 4: Contact holes were opened by wet etching in buffered HF solution.

Step 5: 0.6 μm-thick aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes. Next, a sintering process was performed in N_2 for 30 min at $400^{\circ}C$ to make firm contact between electrodes and piezoresistors.

Step 6: Crossbeam pattern was defined by photolithography using a double-sided mask aligner. Then, frontside deep reactive ion etching (D-RIE) process was performed to a depth of 40 μm. Finally, the cavity and overload-stopper were formed by D-RIE from the backside. Thick photoresist was adopted as passivation layer during D-RIE process.

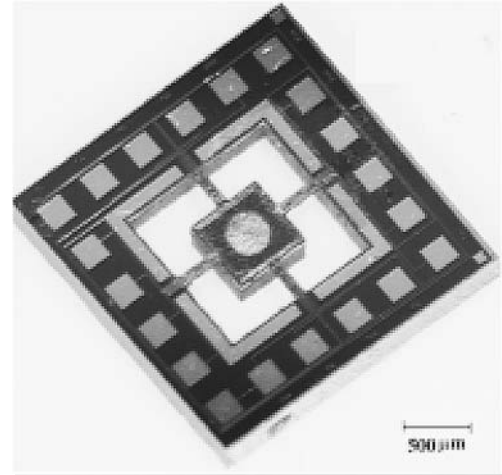Figure 5 is a micrograph of a fabricated sensing chip.

Fig.5 Micrograph of sensing chip

Table 1. Resistance changes of normal piezoresistors and output voltages of shear piezoresistors

	Fx-bridge		Fy-bridge		Fz-bridge				My-bridge				Mx-bridge				Mz-circuit	
	R_{Fx1}	R_{Fx2}	R_{Fy1}	R_{Fy2}	R_{Fz1}	R_{Fz2}	R_{Fz3}	R_{Fz4}	R_{My1}	R_{My2}	R_{My3}	R_{My4}	R_{Mx1}	R_{Mx2}	R_{Mx3}	R_{Mx4}	R_{Mz1}	R_{Mz2}
Fx	+	−	0	0	+	+	−	−	+	+	−	−	0	0	0	0	+	−
Fy	0	0	+	−	0	0	0	0	0	0	0	0	+	+	−	−	0	0
Fz	=	=	=	=	+	−	−	+	+	−	−	+	+	−	−	+	0	0
My	0	0	0	0	+	−	+	−	+	−	+	−	0	0	0	0	+	−
Mx	0	0	0	0	0	0	0	0	0	0	0	0	+	−	+	−	0	0
Mz	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	=	=

CALIBRATION

Calibration of the sensor was performed. An ultra small load indenter (Shimadzu Co., DUH201), controlled by a computer, was used to generate precise force for the calibration. The force Fz was calibrated by applying directly the indenter to the center of the sensing chip.

To calibrate moments Mx (or My), L-shaped Si rod was made, (Fig. 6 (a)). The end of the shorter edge was bonded to the central plate of the sensor so that the longer edge is parallel to the Y- (or X) direction. Then the calibration force F from the indenter was applied to a point adjacent to the end of the longer edge. Consequently, a force Fz and a moment Mx (or My) were generated at the central plate of the sensor. The calibration results have confirmed that these components (Fz, Mx of My) were detected separately.

Similarly, for calibration of Fx (or Fy), U-shaped Si rod was prepared and one end of it was bonded to the central plate. Calibration force F was applied at the other end, (Fig. 6 (b)).

Finally, to calibrate Mz, we used the same rod as for Fx-calibration and the calibration force F was applied at point A,
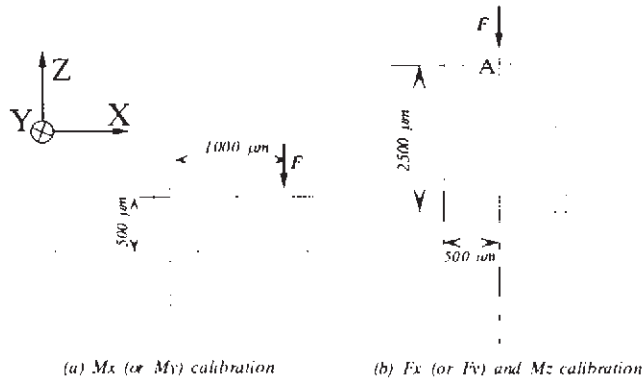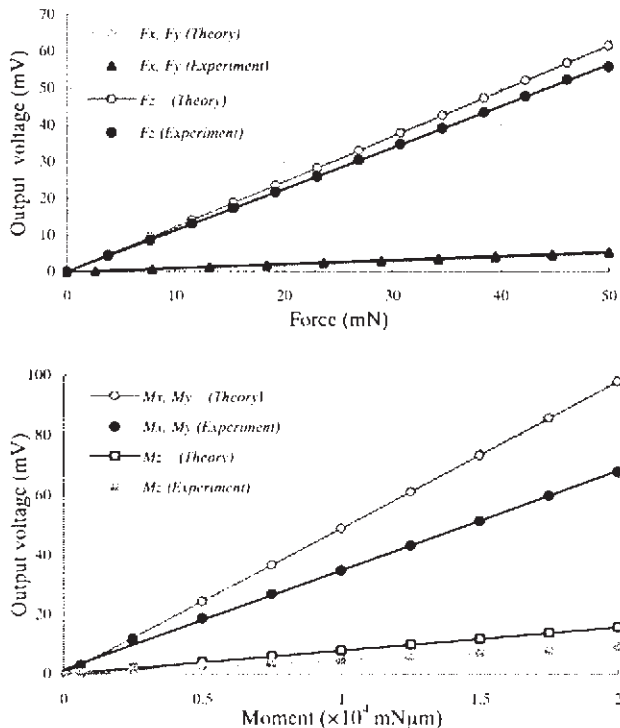
(Fig. 6 (b)), in the direction perpendicular to the plane containing 3 edges of the U-shaped rod. Figure 7 shows the calibration results of six components of force and moment, (input voltage: 5V, temperature: 25°C). The theoretical outputs (calculated based on FEM, book values of piezoresistive coefficients, and circuit sensitivities) are also displayed in this figure for reference. A good agreement between the design and experimental values was obtained. The sensitivities (S) of each components are: $S_{Fz} = 1.15$ mV/mN, $S_{Fx} = S_{Fy} = 0.11$ mV/mN, $S_{Mx} = S_{My} = 3.4 \times 10^{-3}$ mV/mNµm, and $S_{Mz} = 4.6 \times 10^{-4}$ mV/mNµm. The sensing chip has been designed for application in hydraulics, where the horizontal force Fx (or Fy) is much larger than vertical force Fz, so the structural stiffness in horizontal direction was higher than that in the vertical one. These sensitivities can be balanced by changing the beam dimensions. The maximum non-linearity (NL) of each components are $NL_{Fx} = NL_{Fy} = 1.02$ %F.S., $NL_{Fz} = 0.5$ %F.S., $NL_{Mx} = NL_{My} = 2.5$ %F.S., and $NL_{Mz} = 1.62$ %F.S.

CONCLUSIONS

The theoretical investigation, design, fabrication, and calibration of a 6-DOF force-moment sensing chip have been presented. By combining normal and shear piezoresistors in Si (111), and the way of arranging and connecting appropriately their number was considerably reduced in comparison with prior art 6-DOF piezoresistive force sensors known to the authors; consequently, the sensing chip is smaller, more sensitive, and consumes less power. Calibration for six components of force versus output voltages was carried out. The sensitivities are linear, close to the design values, and high enough to measure the forces and moments expected to act on particles in the slow flows of interest in our research. The application of the sensor to turbulent flow in geophysics is now being carried out, and the useful measurement results are expected.

ACKNOWLEGDGMENT

(a) Mx (or My) calibration   (b) Fx (or Fy) and Mz calibration

Fig. 6 Generation of loads for calibration

Fig. 7 Output voltages versus applied loads

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